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Evaluation of the physiological benefits of a passive back-support exoskeleton during lifting and working in forward leaning postures

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ABSTRACT

Musculoskeletal disorders affecting the back are highly prevalent in fields of occupation involving repetitive lifting and working in forward leaning postures. Back-support exoskeletons are developed to relieve workers in physically demanding occupations. This study investigates the physiological effects of a lightweight exoskeleton which provides support through textile springs worn on the back. We hypothesized that wearing such a passive back-support exoskeleton reduces muscle activity of the back and hip muscles, while not influencing abdominal muscle activity and movement kinematics during typical occupational tasks.

We collected electromyography data from the main back and hip muscles as well as whole body kinematics data via optical motion tracking during a set of relevant weight lifting tasks corresponding to typical work conditions. In our sample of 30 healthy volunteers, wearing the exoskeleton significantly reduced muscle activity, with reductions up to 25.59% during forward leaning and 20.52% during lifting in the main back and hip muscles (Erector Spinae at thoracic and lumbar level and Quadratus Lumborum). Simultaneously, no changes in knee and hip range of motion were observed. The stretch of the textile springs correlated with the body mass index and chest circumference of the wearer, and depended on posture, but not on the lifted load.

The LiftSuit exoskeleton relieved back and hip muscles during typically straining occupational tasks, while biomechanical parameters were preserved. This suggests that passive lift-support exoskeletons can be safely used to relieve workers during lifting and forward leaning tasks.

1. Introduction

Heavy physical work including the manual handling and repetitive lifting of loads, as well as frequently working in non-ergonomic positions can lead to injuries or chronic musculoskeletal disorders (Da Costa and Vieira, 2010; Sauter et al., 2021). These conditions can significantly impair the quality of life and the ability to work for the affected individuals, and as such generate an important financial burden to the society. According to survey data and accident statistics 41% of workers in the European Union suffer from back-related musculoskeletal disorders (Kok et al., 2019). The US Labor Bureau found that 31% of days away from work were caused by musculoskeletal disorders (U.S. Bureau of Labor Statistics, 2016). Musculoskeletal disorders affecting the back are most prevalent in fields of occupation that involve working in forward leaning postures or include repetitive lifting of external loads (Kok et al., 2019).

Wearable technology such as back-support exoskeletons have been developed as a promising solution to provide physical support during strenuous tasks, and have the potential to reduce the prevalence of back pain complaints and the consequential lost workdays (Bär et al., 2021; De Bock et al., 2022; Kermavnar et al., 2021). During both lifting and forward leaning tasks, the mass of the upper-body is located in front of the hips, creating a torque around the hip joint and at every level of the spine (Takahashi et al., 2006). To remain at equilibrium in these positions, the back and hip muscles contract and generate torque equal to and in the opposite direction of the torque created by gravity. Back-support exoskeletons aim to create an additional force parallel to the muscles to contribute to this gravity opposing torque, with the advantage of having a more beneficial lever arm than the human muscles.

In the last years, both active and passive back-support exoskeletons have been proposed and evaluated (Ali et al., 2021; De Bock et al., 2022; Golabchi et al., 2022). Active exoskeletons typically rely on electromagnetic motors, series elastic actuators, or artificial muscles to provide assistance (Poliero et al., 2020; Xinyu et al., 2020). While with such systems large forces can be generated, their weight and geometry, as well as the requirement for a power source make these system less

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suitable for use during sustained physical work. Passive back-support exoskeletons can be made much lighter, relying on passive elements such as flexible beams (Alemi et al., 2019; Chang et al., 2020; Koopman et al., 2020; Näf et al., 2018), or rubber bands (Abdoli-E et al., 2006; Lamers et al., 2018), which can be integrated into textile for compact, comfortable and relatively inexpensive solutions.

Recent literature reviews show that a variety of back-support devices have been evaluated, demonstrating positive effects in terms of reduction of back muscle activity during load lifting and forward leaning (Bär et al., 2021; De Bock et al., 2022; Theurel and Desbrosses, 2019). Nevertheless, while evaluation protocols for wearable support systems should ideally be designed to represent relevant occupational tasks and be standardized enough to generate reproducible and comparable results (Torricelli et al., 2020), most studies used simplified protocols not corresponding to realistic use-cases and only considering a subset of tasks. In addition, too little is know about the impact of such exoskeletons on joint kinematics, neuromuscular coordination (Bär et al., 2021; Theurel and Desbrosses, 2019) (e.g., how muscle groups not involved in the task may be influenced), as well as on the factors influencing how support is provided to a specific user. Carefully considering these points is essential, as wearable exoskeletons should only minimally impede natural movements, nor generate compensatory patterns that could generate pain or injuries in other body parts.

In the current study we evaluate the effect of a novel passive back-support exoskeleton, the LiftSuit2.0 (Auxivo AG, Switzerland), on muscle activity and movement kinematics during working in forward leaning positions and repetitive lifting, two typical tasks encountered in industrial physical work. We hypothesized that wearing the exoskeleton can help reducing muscle activity of the back and hip muscles (1), while not influencing abdominal and leg muscle activity (2) and movement kinematics (3). Furthermore, we investigated the support provided by the exoskeleton, as reflected by the stretch of the textile springs providing the assistance, with the expectation that the provided support may depend on the biometric characteristics of the participant, as well as on the manipulated external load. This work is important as it provides novel evidence on the physiological effects of passive exoskeletons, paving the way for wider adoption of such technologies as a mean to support workers during strenuous tasks.

2. Methods

2.1. Back-support exoskeleton

This study was conducted with a prototype of the LiftSuit2.0 (Fig. 1a), an improved version of the LiftSuit1.1 evaluated by Goršič et al. (2022). In brief, the lightweight (~1 kg) passive exoskeleton provides support through two textile springs placed parallel to the back muscles. The exoskeleton is designed to support the back muscles, while not generating the movement for the wearer. The force provided is transferred to the body through the textile interface, which has attachment points at the chest and thighs. The LiftSuit can be adjusted to the users thigh, hip and chest circumference and torso length. Changes in material make the v2.0 more breathable, solving issues with heat development and an optimized cut makes the v2.0 more ergonomic for long-time use. In the v2.0 the placement of the textile springs is guided by bands at the upper back, ensuring correct placement on the wearers back and not on the shoulder. Improper positioning of the exoskeleton, could decrease its ability to provide support.

2.2. Protocol

Participants signed informed consent and measurements were conducted in line with the Declaration of Helsinki. The study protocol was approved by the institutional ethics commission of ETH Zurich (no. 2021-N-151). Participants were instructed on exoskeleton adjustment/use and were encouraged to familiarize themselves with exoskeleton use by walking around and lifting the external loads. Subsequently, sensors were applied and calibrated, normalization values were obtained and participants performed a series of tasks. The experimental protocol was design with the objective of testing the exoskeleton in a set of tasks that is representative of its intended use cases during physical work, and being comparable to existing literature on exoskeleton evaluation, in an attempt to support benchmarking efforts (Torricelli et al., 2020). We followed recommendations from De Bock et al. (2022) and selected dynamic (lifting) and isometric (forward leaning) tasks, and in parallel to whole body kinematics and EMG, collected qualitative user feedback in a subset of participants.

Moreover, participants performed series of five lifts with the exoskeleton without textile springs (control condition) and with the exoskeleton activated (i.e., textile springs under tension). To test the influence of the external load on the support provided by the exoskeleton external loads of different masses (6 kg, 12 kg and 20 kg) were used. Participants were instructed to use semi-squat lifting technique, which is recommended for daily lifting (Wang et al., 2012). Semi-squat lifting was defined as lifting with moderate knee flexion (90° knee flexion) and trunk inclination (45° trunk flexion), see Fig. 2. Instruction on lifting technique was performed prior to task execution using example pictures and a live demonstration by the experimenter. The lifting movement was guided by a computer generated voice, pacing the lifting at 5 s per lift cycle. At least one practice round was performed to get acquainted with voice guidance. The order of the conditions was randomized.

Another straining movement often observed in occupational fields such as nursing, agriculture and baggage handling, is forward leaning. To asses such work, participants held unloaded static forward leaning positions of 30° and 60° for 15 s, while standing and kneeling.

The following biometric parameters were measured: height (m), torso length (greater trochanter to collar bone; m), weight (kg), chest circumference (m), hip circumference (m) and thigh circumference (m). Participants who participated during the latter half of data collection (questionnaire included after interim analysis) answered usability questions after completion of each task: "Do you feel supported by the LiftSuit? (yes; a little; almost not; no; unsure)" and "Do you feel constrained by the LiftSuit? (yes; a little; almost not; no; unsure)". As well as, a question after completing all tasks: "Do you like the support provided by the LiftSuit? (It makes work harder; I feel no support; I feel support, but too little; I feel a clear support, but would like more; The support was exactly right)".

Muscle activity of seven of the main muscles, respectively muscle groups, involved in lifting tasks was measured on the right side of the body: Erector Spinae at thoracic (EST) and lumbar level (ESL), Quadratus Lumborum (QL), Gluteus Maximus (GM), Biceps Femoris (BF), Semitendinosus (ST), Rectus Abdominis (RA). Trigno sensors were used to record surface electromyography (EMG) at 2048 Hz (Delsys Ltd, Natick, United States). These muscles were selected for their involvement in creating a torque around the hip and spine (EST, ESL, QL, GM, BF, ST) or to control for potential compensatory muscle activity (RA). Prior to the experiment, two series of maximal voluntary muscle contractions were performed, with > 1 min between contractions of the same muscle. The average of the two attempts was used for normalization.

Movement kinematics was captured using an optical motion capture system (Optitrack, NaturalPoint, USA) using 15 cameras recording full-body movement based on 58 optical markers at 120 Hz. Calibration and marker placement were performed according to the supplier documentation (C-motion Inc., 2020). Additionally, markers were placed on the external loads and textile springs.

2.3. Data processing

The EMG data was post-processed in line with European recommendations for surface EMG (Hermens et al., 1999) using MATLAB

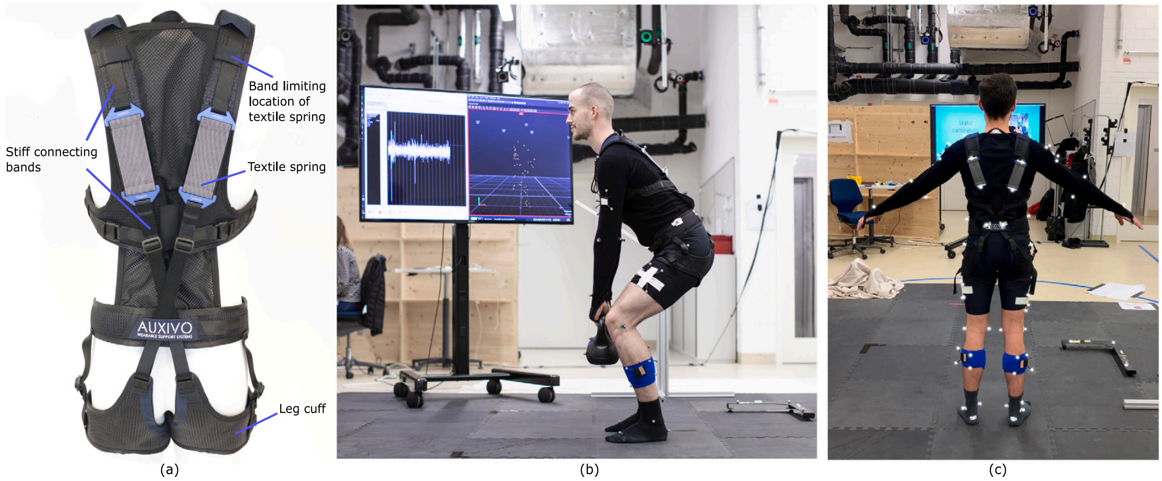

Fig. 1. (a) The textile springs of the exoskeleton are located on the participants back and stretch when leaning forward. The force of the textile springs is transferred through the stiff connecting bands and transferred to the body through the vest at the chest and the leg cuffs. Horizontal bands limit the location of the textile springs for correct placement on the back of the participant. (b) Muscle activity and kinematics were recorded during lifting with different external loads. (c) Full-body movement was recorded using on 58 optical markers, with additional optical markers placed on the external load and the textile springs of the exoskeleton.

R2019b (MathWorks, USA). The raw data was filtered bidirectionally with a bandpass (10 Hz - 500 Hz) butterworth filter. For the lifting task a linear envelop was created by lowpass filtering (butterworth; 3 Hz) the rectified data. Trajectory data of the external load was used to determine the moment the external load left the ground (25% of the lift cycle, Fig. 2). Single lifts were defined as 1 s before until 4 s after this event. For each lift the peak muscle activity was determined as a measure of maximal activity, and the area under the curve was calculated as a measure of total muscular effort. The voice guidance left some uncertainty regarding the moment the task start therefore the median of the 2nd to 5th lift is reported. For the leaning task the root mean square over the middle 10 s of the task is reported.

The motion capture data was labeled using Motive 2.0.0 (NaturalPoint, USA) and analyzed using Visual-3D (C-Motion, USA). For the anatomical model, body segments were defined using both markers placed on bony landmarks and cluster markers placed on the segments. Body segment trajectories were calculated using cluster markers only. To assess the influence of the exoskeleton on lifting kinematics we report range of motion (ROM) of the hip and knee joints. For each lift the min and maximum angle were determined using a peak-finder.

2.4. Statistics

The exoskeleton performance indicators were the differences in muscle activity and joint ROM between control to exo active condition. Two-way repeated-measures ANOVA testing was performed. For the lifting task the response variables were peak muscle activity, muscle activity effort and hip and knee joint ROM. The influence of the independent factors (mass of the external load [Load] and the presence or absence of the textile springs [Exo]), as well as the Load*Exo interaction are reported. For the leaning task the response variable was the root mean square muscle activity. The influence of the independent factors (body angle [Angle] and the presence or absence of the textile springs [Exo]) as well as the Exo*Angle interaction are reported. Pearson correlation analysis was performed to analyze the correlation between stretch of the textile springs and participants biometric characteristics. The test outcomes were considered significant if $p < 0.05$.

3. Results

3.1. Sample

Data was collected from 30 healthy volunteers (8 female) who were novel to back-support exoskeletons. Participants were between 20 and 62 years old (Mean: 27.2 y; SD: 7.6 y), with body heights between 1.64 and 1.94 m (Mean: 1.78 m; SD: 0.71 m) and body weights between 54 and 102 kg (Mean: 72.9 kg; SD: 12.3 kg).

3.2. Lifting

During lifting, the exoskeleton significantly reduced peak muscle activity of the lower back muscles (Fig. 3a and Table 1). The reduction ranged from 6.83 to 14.23% for the ESL ($p_{exo} < 0.01$) and from 10.74 to 20.52% for the QL ($p_{exo} < 0.05$). For the ESL no interaction between external load and exoskeleton was observed ($p_{load*exo} = 0.54$). The peak muscle activity increased when lifting heavier loads, but reductions in muscle activity when wearing the activated exoskeleton were observed independent of external load (Fig. 3a). Similar results were observed when looking at the total lower back muscle effort during the lifting cycle (Fig. 3b and Table 1). Reductions in muscular effort ranged from 5.36 to 9.61% for the ESL ($p_{exo} < 0.001$) and from 6.61 to 9.22% for the QL ($p_{exo} < 0.01$). Statistically significant reductions in hip muscle effort were observed, but the % reduction in effort was limited ranging from 1.21 to 6.17% ($p_{exo} < 0.05$).

The effect of the exoskeleton on RA activity was not statistically significant ($p_{exo} = 0.27$) and no interaction between external load and exoskeleton was observed ($p_{load*exo} = 0.29$, Table 1). Significant increases in semitendonosus activity were observe with increased external load, but no significant effect of the exoskeleton on this muscle was detected (Fig. 3a). The maximum and minimum joint angle of the hip and knee joint were not significantly different, suggesting the ROM was not influenced by the activated exoskeleton (Fig. 3(c, d)).

3.3. Forward leaning postures

Significant reductions in back and hip muscle when activating the LiftSuit were observed during forward leaning (Fig. 4 and Table 2). When leaning forward in standing position, such as common in nursing and agriculture, the ESL activity was reduced by 8.38% at 30° and 12.48% at 60° ($p_{exo} < 0.01$). When leaning forward in kneeling position, such as common in building tasks like tile laying, the ESL activity was reduced by 12.10% at 30° and 18.80% at 60° ($p_{exo} < 0.001$). Similar reductions in muscle activity were observed for the QL ($p_{exo,\ standing} < 0.01$, $p_{exo,\ kneeling} < 0.05$) and the EST ($p_{exo,\ standing} < 0.01$, $p_{exo,\ kneeling} < 0.05$). No significant effect of the exoskeleton on QM and leg muscle activity was observed during forward leaning in either position. Levels of RA activity in this task were minimal ($M_{activity} < 5\%MVC$ in all conditions) and no effect of the exoskeleton on RA activity was observed.

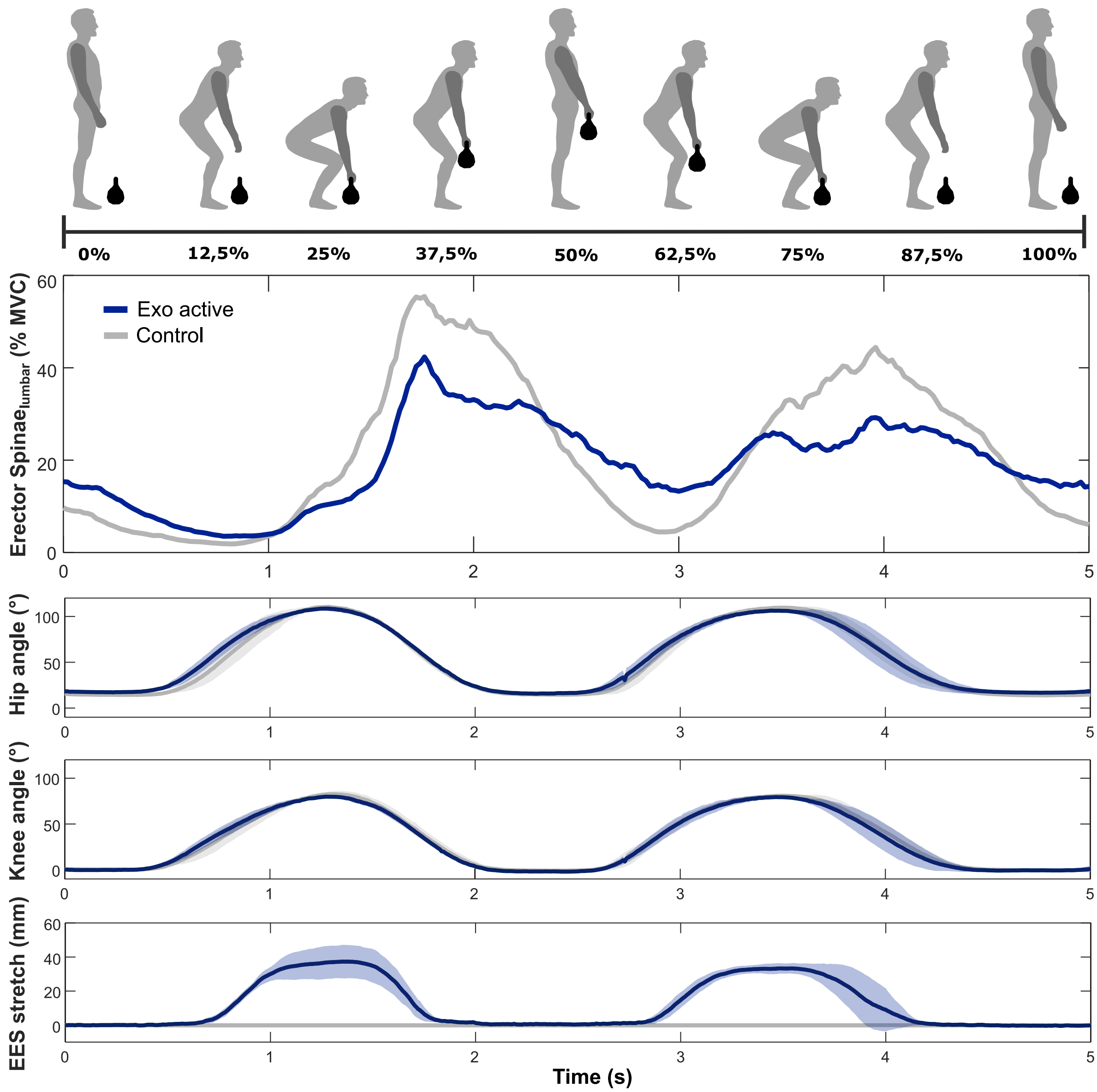

Fig. 2. Data of one representative participant lifting without the support of the exoskeleton (gray) and with the support of the exoskeleton (blue). This figure shows the timing of peak support in relation to movement kinematics and lower back muscle activity. There are two peaks in back muscle activity related to the moment of lifting and lowering the external load. The textile spring is stretched by the posture change of the participant, with the supporting force peaking at the deepest point of the lift. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Correlation with biometric characteristics

During leaning postures the stretch of the textile springs was significantly correlated with body mass index (BMI; $r_{standing}$ = 0.50, $r_{kneeling}$ = 0.48), chest circumference ($r_{standing}$ = 0.46, $r_{kneeling}$ = 0.44), weight ($r_{standing}$ = 0.43, $r_{kneeling}$ = 0.42) and thigh circumference ($r_{standing}$ = 0.40, $r_{kneeling}$ = 0.40), but not with height or torso length (Table 3). During lifting, the stretch of the springs correlated with BMI ($r_{lifting}$ = 0.36) and a trend towards correlation with chest circumference was observed ($r_{lifting}$ = 0.50, $p_{lifting}$ = 0.058).

3.5. Usability

Fourteen participants completed a usability questionnaire. Half of the participants answered that the level of support provided by the LiftSuit was just right. The other half felt the support, but would have preferred more support (35.7%) or did not perceive support (14.3%). More participants reported feeling well supported during lifting (71%), than during forward leaning (57%). Most participants reported that the LiftSuit did not (64.3%) or almost not (21.4%) hinder their movement.

4. Discussion

The objective of this work was to evaluate the physiological effect of a back-support exoskeleton on movement kinematics and muscle activity. The data confirms our hypothesis that wearing the exoskeleton reduces muscle activity of the main back and hip muscles. Specifically, we observed significant reductions in peak activity and muscle effort of the ESL during both dynamic and static tasks. In addition, muscle activity of the EST, QL and GM were reduced during lifting and the EST and QL were reduced during forward leaning. This suggests the exoskeleton supports the torso from hip to upper back during demanding occupational tasks. Compared to data collected with the LiftSuit1.1 (Goršič et al., 2022), our study using the LiftSuit2.0 additionally observed changes in lower back muscle activity, while maintaining a similar level of support in the ESL. The 14.2% reduction in ESL activity observed in

Table 1
Mean (M) and standard deviation (SD) of the change in muscle activity (control condition - exo active) during repetitive lifting expressed in %MVC and %control condition. Changes were considered significant if the *p*-value of the 2-way repeated-measures ANOVA with independent factors Load and Exo was <0.05. Muscles for which there was a significant effect of Exo are formatted in bold font.

Effort (integral of lift)	Δ EMG (%Control)						ANOVA *p*-values		
	6 kg		12 kg		20 kg				
	M	SD	M	SD	M	SD	Load	Exo	Int
Erector Spinae$_{thoracic}$	**15.73**	**18.58**	**11.90**	**20.47**	**11.66**	**20.00**	**<0.001**	**<0.01**	**0.30**
Erector Spinae$_{lumbar}$	**7.17**	**12.55**	**9.61**	**13.72**	**5.36**	**11.72**	**<0.001**	**<0.001**	**0.38**
Quadratus Lumborum	**6.61**	**26.67**	**6.83**	**20.28**	**9.22**	**16.07**	**<0.001**	**<0.01**	**0.99**
Gluteus Maximus	**6.17**	**13.06**	**1.21**	**13.72**	**5.21**	**12.63**	**<0.001**	**<0.05**	**0.53**
Biceps Femoris	0.86	13.15	0.6	16.82	0.86	14.61	0.41	0.38	0.90
Semitendinosus	1.59	25.29	−0.94	22.90	2.39	22.87	<0.001	0.51	0.50
Rectus Abdominis	−17.31	55.38	17.59	39.93	−13.08	53.32	0.34	0.32	0.26
Peak activity	M	SD	M	SD	M	SD	Load	Exo	Int
Erector Spinae$_{thoracic}$	7.36	27.27	4.75	26.50	5.63	20.52	<0.001	0.06	0.62
Erector Spinae$_{lumbar}$	**14.23**	**15.99**	**13.50**	**31.57**	**6.83**	**16.72**	**<0.001**	**<0.05**	**0.54**
Quadratus Lumborum	**20.52**	**38.76**	**13.33**	**31.54**	**10.74**	**26.97**	**<0.01**	**<0.05**	**0.46**
Gluteus Maximus	5.49	23.08	1.87	24.62	5.94	15.54	<0.001	0.10	0.50
Biceps Femoris	4.09	18.33	0.44	15.36	0.37	18.14	0.56	0.56	0.70
Semitendinosus	7.75	44.20	−5.01	48.47	−5.33	37.01	<0.01	0.87	0.15
Rectus Abdominis	−7.24	59.82	−54.14	88.07	−19.29	137.40	9.24	0.27	0.29

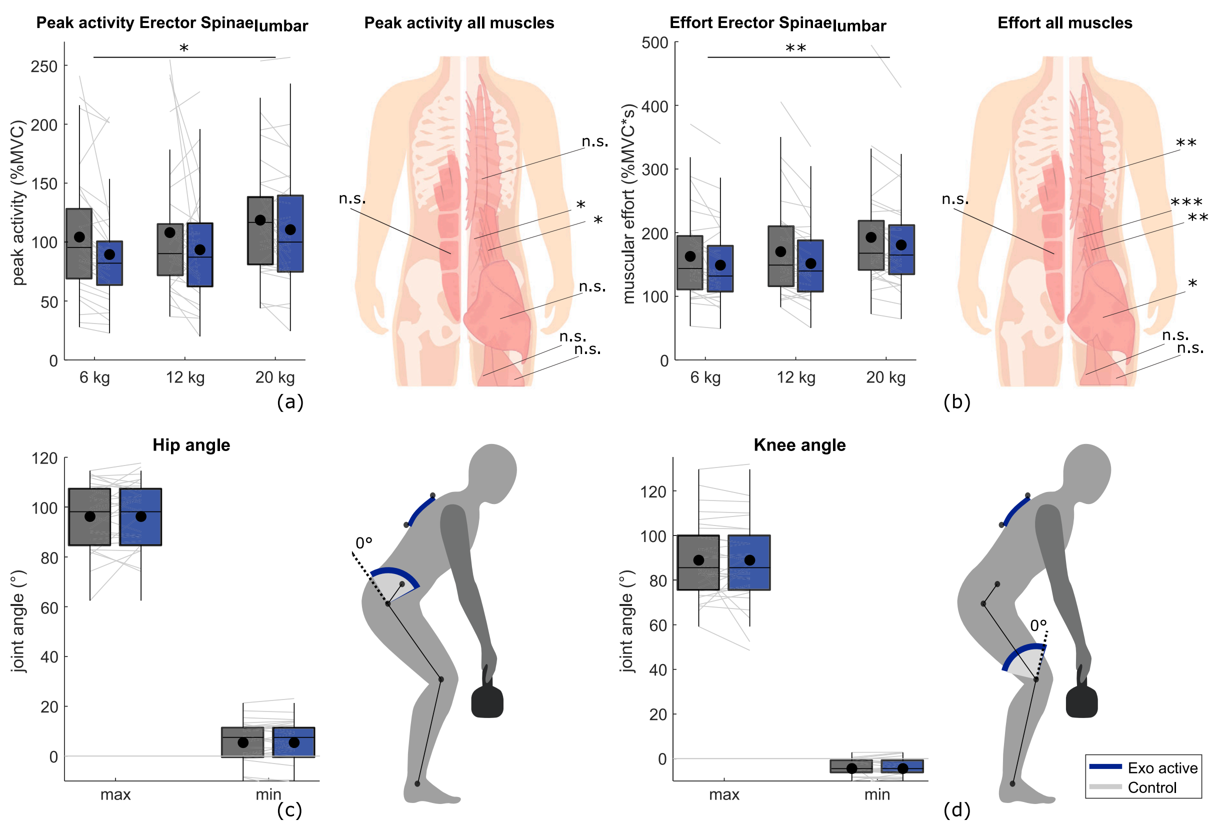

Fig. 3. Muscle activity and kinematics during lifting of different loads with the exoskeleton activated (blue) and during the control condition (gray) at group level ($n = 30$). The box plots present details of the ESL (a, b) or individual joints (c, d) while the graphical representation reports statistical significance for all other muscles (a, b) or provides visual support (c, d). Gray lines are individual data, dot is the sample mean. Stars indicate significant effect of the factor Exo in the 2-way repeated measures ANOVA (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). (a) Peak muscle activity in the ESL (b) Muscle effort of the ESL, calculated as integral of the entire lift. (c) Maximal and minimal hip joint angles while lifting 6 kg. (d) Maximal and minimal knee joint angles while lifting 6 kg. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

this study is similar to what has been reported with another exoskeleton using rubber bands (Herowear APEX, 15% reduction, (Goršič et al., 2021)), while larger exoskeleton using flexible beams can provide additional support (VT-Lowe, 29% reduction, Alemi et al. (2019)).

Our finding that the exoskeleton does not influence leg and abdominal activity, or hip and knee kinematics, confirm our hypothesis that exoskeleton use does not lead to compensatory movement patterns. By leaning forward, gravity can be used to tension the springs, and thus no abdominal activity is needed. This effortless stretching of the springs requires the hip torque generated by the springs to be lower than the torque generated by the torso mass under the influence of gravity. This is an interesting advantage of spring-based exoskeletons over, for example, beam-based solutions such as the VT-Lowe exoskeleton, where increase in external oblique activity was reported (Alemi et al., 2019), likely caused by the stiffness of the beam being so high that they cannot be bent using gravity alone.

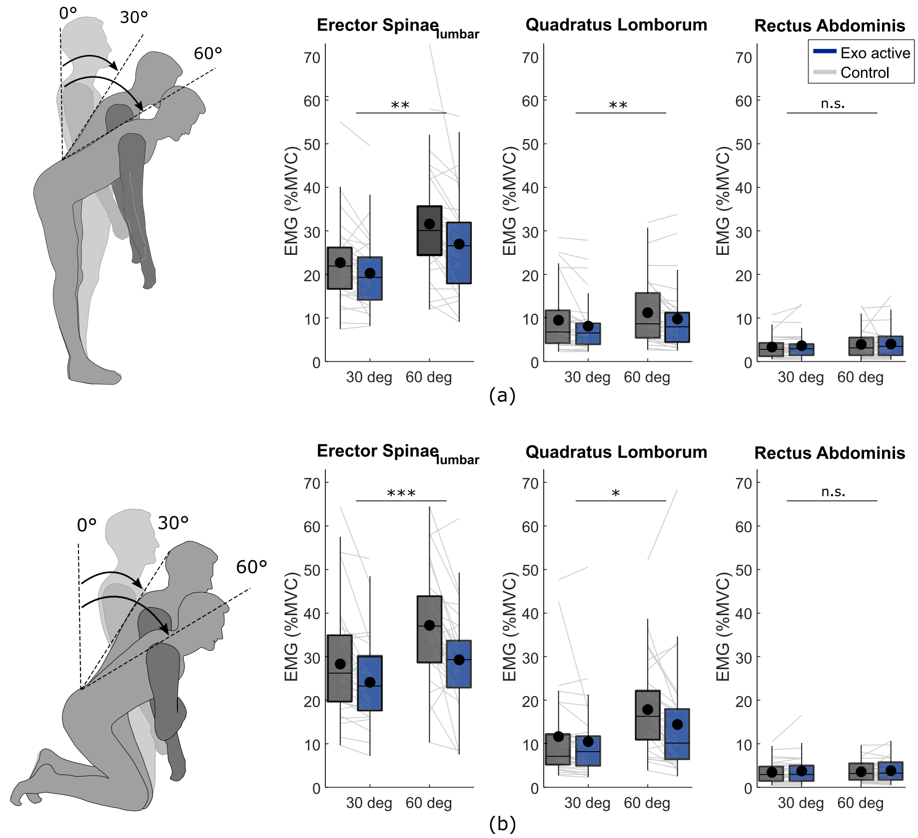

Fig. 4. The root mean square of the muscle activity during forward leaning in standing (a) and kneeling (b) position with the exoskeleton activated (blue) and during the control condition (gray) at group level (n = 30). The box plots present details of the lower back muscles (ESL and QL) involved in holding the position and the RA to visualize potential compensatory activity. Gray lines are individual data, dot is the sample mean. Stars indicate significant effect of the factor Exo in the 2-way repeated measures ANOVA (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Mean (M) and standard deviation (SD) of the change in muscle activity (control condition - exo active) during the static forward leaning task expressed in %MVC and %control condition. Changes were considered significant if the 2-way repeated-measures ANOVA with independent factors Angle and Exo resulted in $p < 0.05$. Muscles for which there was a significant effect of Exo are formatted in bold font.

Standing	Δ EMG (%Control)				ANOVA p-values		
	30 °		60 °				
	M	SD	M	SD	Angle	Exo	Int
Erector Spinae$_{thoracic}$	**19.98**	**30.90**	**25.59**	**32.40**	**<0.001**	**<0.01**	**<0.05**
Erector Spinae$_{lumbar}$	**8.38**	**19.46**	**12.48**	**18.71**	**<0.001**	**<0.01**	**0.09**
Quadratus Lumborum	**10.2**	**16.44**	**13.66**	**17.96**	**<0.01**	**<0.01**	**0.88**
Gluteus Maximus	4.05	29.73	0.75	37.51	0.15	0.78	0.92
Biceps Femoris	−6.12	43.05	−2.91	54.91	<0.001	0.92	0.47
Semitendinosus	−15.67	54.96	−2.71	31.47	<0.01	0.97	0.43
Rectus Abdominis	−5.72	23.25	−7.35	37.63	0.17	0.45	0.75
Kneeling							
Erector Spinae$_{thoracic}$	**15.58**	**32.67**	**12.50**	**42.79**	<0.001	**<0.05**	**0.47**
Erector Spinae$_{lumbar}$	**12.10**	**17.77**	**18.80**	**26.90**	**<0.001**	**<0.001**	**<0.01**
Quadratus Lumborum	**6.34**	**18.15**	**22.43**	**26.09**	**<0.001**	**<0.05**	**<0.05**
Gluteus Maximus	−3.44	29.54	6.40	22.72	0.06.	0.57	0.06
Biceps Femoris	−5.36	26.15	−7.00	80.31	<0.001	0.38	0.13
Semitendinosus	−16.17	39.35	−9.70	54.30	<0.001	0.37	0.40
Rectus Abdominis	−5.52	15.91	−8.14	41.37	0.77	0.18	0.77

While lifting loads with the exoskeleton, the maximal and minimal hip and knee angles were similar to lifting without the exoskeleton. Specifically, no tendency to change lifting technique from semi-squat lifting posture to stoop lifting posture was observed. This is important, because changes in lifting posture might affect the loading of the spine in the lumbar region (Von Arx et al., 2021), and influence the development of muscle fatigue (Wang et al., 2012). Several studies reported objectively measured or perceived changes in lifting technique when lifting with exoskeletons using flexible beams at spine level (Baltrusch et al., 2019; Näf et al., 2018). Reduced knee, hip and trunk were reported during some, but not all lifting tasks (Näf et al., 2018; Koopman et al., 2020; Amandels et al., 2018), and affected lumbar flexion in one study (Koopman et al., 2020). Changes in lifting technique were reported for the previous LiftSuit version (Goršič et al., 2022). The

Table 3
Correlation between biometric characteristics and stretch of the textile springs. Pearson correlations coefficients (r) were considered significant if the $p < 0.05$ and are formatted in bold font.

Biometric	Standing		Kneeling		Lifting	
	r	p	r	p	r	p
Height	0.21	0.270	0.22	0.244	−0.05	0.810
Torso length	0.13	0.487	0.24	0.202	−0.01	0.960
Weight	**0.43**	**<0.05**	**0.42**	**<0.05**	0.20	0.290
Body Mass Index	**0.50**	**<0.01**	**0.48**	**<0.01**	**0.36**	**<0.05**
Chest circumference	**0.46**	**<0.05**	**0.44**	**<0.05**	0.35	0.058
Hip circumference	0.33	0.079	0.31	0.099	0.16	0.408
Thigh circumference	**0.40**	**<0.05**	**0.40**	**<0.05**	0.14	0.471

difference to our findings likely comes from the LiftSuit2.0 having more comfortable leg cuffs, as well as lower placement of the springs leading to less stiffness around the hip. In general, the more compliant textile exoskeletons might be preferred to exoskeletons with rigid components, such a flexible beams, because they are less likely to restrict wearers movement freedom, ultimately leading to better comfort and working ergonomics.

As can be observed in Fig. 2, the peak of the supporting force provided by the exoskeleton occurs at the deepest point of the lift, while the peak of the back muscle activity occurs when the user grasps the load and accelerates it against gravity. This can be seen as a limitation of passive exoskeletons relying on trunk flexion to generate power, whereas active exoskeletons could customize assistance and provide it regardless of trunk flexion. On the other hand, there seems to be a trade-off between the level of support provided by back-support exoskeletons and wearer comfort. In exoskeletons with rigid components the force at the interfaces are perpendicular to the contact surface, compared to all textile interfaces, which include higher levels of shear force. Since comfort is one of the main criteria for acceptance of exoskeletons in the field (Amandels et al., 2018), back-support exoskeletons are limited in how much support they can provide. Thus, while textile exoskeletons are lighter and offer more freedom of movement, the level of support they can provide is lower. However, even modest reductions in muscle activity, delay development of fatigue and thus may reduce injury risk, especially when considering long periods of usage during work.

We observed a correlation between the stretch of the textile springs and the wearers biometric characteristics, most notably BMI and chest circumference. This implies that users with relatively higher torso mass, who generated larger torques when their torso mass is in front of their hip joint, also received more support. The support provided seems to depend more on parameters that determine the route of the springs and their connecting bands, than on the force applied to the spring by the external load. Thus through the design of the exoskeleton users receive a level of support that is adapted to their biometric characteristics. This is in line with our finding that half of the participants reported the level of support provided by the LiftSuit was just right.

One study limitation is the brief exoskeleton familiarization dictated by a one-session protocol. A build up of exoskeleton use-duration over several days is recommended for first-time users. Often user satisfaction and exoskeleton performance increase during this period. Learning to activate the muscles as needed to work in parallel with the springs likely takes several days, resulting in the user subconsciously relying more on the provided support over time. Furthermore, experienced wearers learn how to adjust the exoskeleton best to their individual physique, thereby optimizing the level of support while minimizing discomfort. Pilot data obtained from experienced users consistently shows higher reductions in muscle activity than observed in the first-time exoskeleton users recruited for this study. These observations should be further confirmed in the context of longitudinal evaluation of the LiftSuit2.0, as well as in field tests with end-users in real work conditions.

5. Conclusion

Spring-based back-support exoskeletons such as the LiftSuit can help reduce muscle activity when lifting loads up to 20 kg and during leaning forward. The exoskeleton did not affect movement kinematics, nor increased muscle activity in muscles not directly involved in the task. This work also underlines how spring-based back-support exoskeletons provide assistance and emphasizes the importance of considering user biometric characteristics and the adaptation of the exoskeleton to the user to optimize comfort and support.

CRediT authorship contribution statement

Rachel M. van Sluijs: Writing – review & editing, , Writing – original draft, Methodology, Formal analysis, Conceptualization, Visualization. **Michael Wehrli:** Writing – review & editing, Formal analysis, Data curation, Visualization. **Annina Brunner:** Writing – review & editing, Formal analysis, Data curation. **Olivier Lambercy:** Writing – review & editing, , Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rachel van Sluijs is employed by Auxivo AG. Olivier Lambercy is an academic advisor to Auxivo AG.

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Ethical standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional guides.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111489.

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